Carrier Unlicensed Radios 2019

Carrier Wi-Fi, LTE-U, LAA, CBRS, LWA, MulteFire

Abstract:

This report provides an updated forecast for Wi-Fi, LAA, LTE-U (MulteFIre) and CBRS radio deployment by carriers. A brief technical background is included for reference. This report illustrates how the unlicensed bands will be used by the mobile operators, with forecasted shipments and revenue for small cells and Carrier Wi-Fi access points.

July 2018

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Carrier Deployments in Unlicensed and Shared Spectrum including Carrier Wi-Fi, LAA, CBRS, and MulteFire Radios

MEXP-UNLIC-19
July 2019

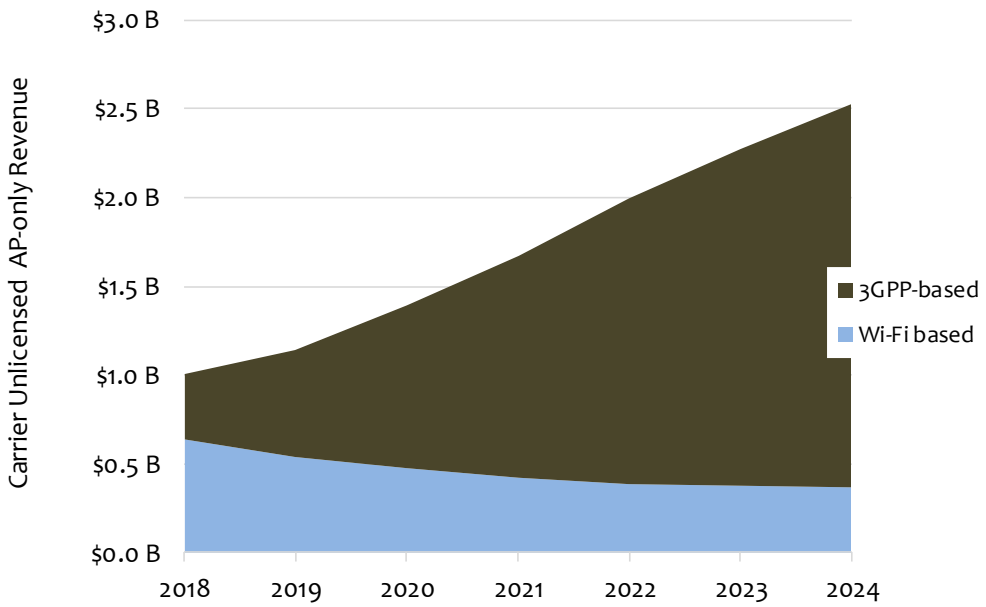
1 EXECUTIVE SUMMARY

Communication Service Providers (CSPs) are starting to invest in the unlicensed bands again. They have used Wi-Fi for many years, but with mixed results. In high density areas, Wi-Fi has become saturated and the operators are not extracting enough capacity to make Wi-Fi an ongoing strategy. Instead, they are starting to turn to LTE-based alternatives.

Last year's 94-page report on this topic provided a significant level of detail on market trends, technology, and changes to the business model. Last year's forecast was pretty accurate, and all of the main technology points and competitor profiles still apply. This year, there's honestly not much that we can add to the insight from last year's report… so we have chosen to focus on the forecast as an update on timing and quantities.

Unlicensed and shared-spectrum options are unfolding, and in addition to the (declining) market for Carrier Wi-Fi, multiple new options are now becoming available for the operators:

- MulteFire, or LTE-U, is now fully standardized and version 1.1 of the specifications has been released. This option allows for full network deployment without owning any spectrum whatsoever, and we expect it to be used internationally for Private LTE networks.
- License-Assisted Access (LAA) has now been launched commercially, and is built into many small cells. LAA extends the capacity of licensed bands by adding channels in the unlicensed bands through Carrier Aggregation.
- CBRS shared spectrum is coming available in the next six months (as another 'unlicensed' option with General Authorized Access licenses), and Priority Access Licenses (PALs) will be auctioned in the first half of 2020. We expect this option to draw new operators such as cable operators into wider networks, and also to be used by the big mobile telcos.
- 5G is also coming to the same unlicensed bands in time. All of the above options will be duplicated for 5G and we should expect a gradual transition to 5G NR in all cases.



Source: Mobile Experts

Chart 1: Carrier Unlicensed Radio AP Equipment Revenue Forecast, 2018-2024

Mobile Experts' report on Private LTE provides more detail on how enterprise networks are likely to be deployed in these bands as well as licensed bands.

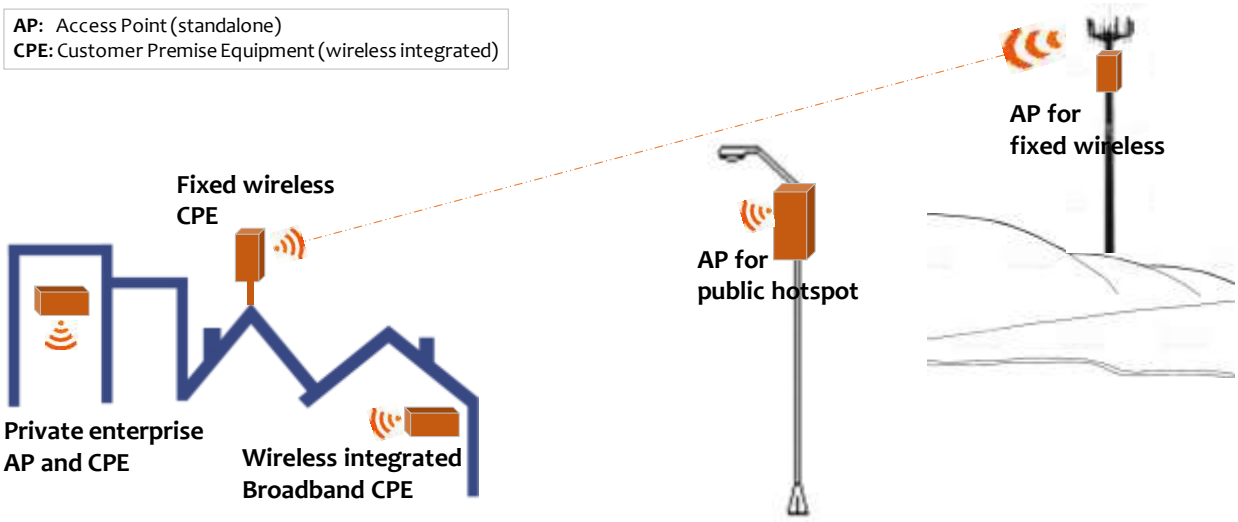
With the transition from Carrier Wi-Fi to 3GPP based technologies, we have seen a slow market between 2016 and 2019, but we expect an uptick with significant growth as a large array of small cells adopt LAA and CBRS.

2 MARKET OVERVIEW

Mobile operators are maximizing the use of their licensed spectrum, and as more unlicensed spectrum appears on the horizon, they are also very interested in taking advantage of unlicensed options. The market driver is simple: Operators want to add capacity to their networks, and unlicensed radio options offer low-cost alternatives.

"Carrier Unlicensed Radio" Market Definition

Wireless is now an extension of any broadband connectivity service whether that's at home or outdoors. Fixed broadband providers like the cable and wireline telco operators increasingly rely on wireless broadband gateways to service a growing number of wireless devices at home such as smartphones, laptops, security cameras, doorbells, etc. The same is true for small businesses--especially those without IT staff. These small businesses largely look to broadband service providers to manage wireless environment inside their premises. While the carrier use of unlicensed radios like Wi-Fi is largely confined to "local area networks" covering a home, for instance, some fixed wireless operators use outdoor radios to cover a wide area. For some, providing public hotspot coverage using standalone Wi-Fi access points provide strategic value-add for fixed or nomadic services.



Source: Mobile Experts

Figure 1. Broad Carrier Unlicensed Radio Equipment Definitions

As shown above, the carrier unlicensed radio equipment generally covers higher-power access point (AP) units for outdoor applications and wireless-integrated customer premise equipment (CPE) like broadband gateways sitting inside homes and businesses. In some cases, a CPE can be high-power units placed outside for fixed wireless applications, but recently large numbers of CPEs have been used by cable operators to create a network of

APs, through millions of "homespots." The sum of these APs and CPEs across the different applications are consider the "carrier unlicensed radios" units.

The Carrier unlicensed radio equipment in the form of standalone APs or wireless CPEs can come in a wide variety of form factors and power levels. While CPEs are mostly low-power indoor units for providing wireless connectivity inside homes and small business buildings, most outdoor APs and CPEs are higher-power radios that can provide greater distances for coverage and reach. For example, some 5 GHz unlicensed radios deployed for fixed wireless applications can operate at 4W EIRP in certain U-NII bands. In contrast, indoor Wi-Fi integrated CPE units may operate at 100-250 mW, depending on each country's rules. Some of the wide variety of carrier unlicensed radio products are shown above.

While a "broad" Carrier Unlicensed Radio market can include all aspects of carrier wireless services as depicted in Figure 1, in this report, we specifically target Carrier Unlicensed Radios used for "mobile and nomadic" applications only. Hence, all fixed wireless access related radios[1] and residential broadband gateway markets are not covered in our "Carrier Unlicensed Radio" forecast except for a small portion of small business CPE-related deployments that are used by mobile/telco/cable operators to provide hotspot coverage to its users for nomadic use.

Expanding Unlicensed Spectrum Horizon

Spectrum is obviously a fundamental resource for wireless services. Unlicensed and shared spectrum resource for fixed wireless access span across from sub-1 GHz to 70/80 GHz millimeter wave bands. This wide range of spectrum options come with caveats on distance reach and speed performance, AP-CPE cost tradeoffs, "$/GB" transport cost, architecture/deployment choices, core network requirements, and many other factors that impact on-going operations of delivering fixed wireless broadband service. One thing is clear. Spectrum is a key determinant of broadband service level (speed and quality), and cost point at which a particular service is delivered.

[1] Mobile Experts provides detailed coverage of fixed wireless market across both licensed and unlicensed spectrum bands using LTE/5G and 802.11-based technologies in our *Fixed Wireless Access* market study.

Spectrum Band	Bandwidth	License Regime	Technology	Interference Risk	Availability (Region)
2.4 GHz (2.40 – 2.49)	~80 MHz	Unlicensed	Wi-Fi (802.11)	High	Now (worldwide)
3.5 GHz (3.55 - 3.70)	150 MHz	Shared (CBRS, USA only)	CBRS, LAA, MulteFire	Medium (GAA)/ Low (PAL)	Late 2019 (GAA) to 2020 (PAL)
5 GHz (5.15 - 5.85)	580 MHz	Unlicensed	Wi-Fi (802.11), LAA, MulteFire	High	Now (worldwide)
6 GHz (5.925 – 7.125)	1,200 MHz	Unlicensed (PROPOSAL)	Wi-Fi (802.11)	Medium - High	N/A (USA, EU)
60 GHz (57 - 71)	14,000 MHz	Unlicensed	Wi-Fi (802.11 ad/ay)	Low – Medium	Now (NA, APAC, expanding)

Source: Mobile Experts

Figure 2. Unlicensed and Shared Spectrum Landscape

The Wi-Fi Alliance and IEEE standards organizations continue to play integral roles in development and promotion of unlicensed spectrum technologies. Meanwhile, the CBRS Alliance and MulteFire Alliance are active promoters of the LTE use in the unlicensed and shared spectrum bands.

2.4 GHz ISM Band

WISPs have used the 2.4 GHz band in the past to take advantage of a large chunk of spectrum in this band. With the popularity of Wi-Fi use indoors and out, the rising noise floor in this spectrum has made its usage problematic in the past. With most Wi-Fi indoor usage moving to the 5 GHz band, some operators are coming back to the 2.4 GHz band as the noise floor has come down somewhat to make this more useful. Like the 900 MHz band, this band is most often used in very rural areas to reach far away subscribers from a base station access point.

3.5 GHz CBRS Band

The *Citizen Broadband Radio Service* (CBRS) provides for shared spectrum use in the 3.5 GHz band. For the first time, dynamic spectrum sharing rules based on the three-tier licensing regime (as shown below) allows commercial use of the band while ensuring interference protection and uninterrupted use by the incumbent users (i.e., military radars and fixed satellite stations). Under the plan, a *Spectrum Access System* (SAS) maintains a database of

all CBRS base stations and coordinates spectrum access among the incumbent and new commercial users. In the three-tier licensing structure, at least 80 MHz of spectrum are designated as *General Authorized Access* (GAA), or unlicensed use, and up to 70 MHz of *Priority Access License* (PAL) are planned to be auctioned off as licensed band shortly.

It should be noted that many WISPs currently use the 3.65 – 3.7 GHz band as temporary "incumbent" users for fixed wireless. By 2020, the use of this particular portion of the band will need to transition under the CBRS three-tier licensing regime.

5 GHz WLAN Band

For many WISPs, the 5 GHz band has been the "workhorse" of delivering fixed wireless broadband access with relatively large amounts of bandwidth available. The 5GHz band spans across several different frequency bands with different usage requirements. For fixed wireless application, many WISPs use "U-NII-2-extended" and "U-NII-3" bands for different reasons. With dynamic frequency selection (DFS), or radar avoidance, requirement, many common Wi-Fi access points typically do not use the "U-NII-2-extended" band. Thus, it is relatively "pristine" unlicensed spectrum upon which to deliver fixed wireless access, especially for operators targeting denser suburban settings. Moreover, this particular band is considered a "worldwide" band as it is designated as unlicensed globally. Hence, it provides a greater market opportunity for vendors to address the global market. Unlike the U-NII-2-extended band, the U-NII-3 band provides a greater transmit power limit. Hence, this is popular among traditional WISPs looking to maximize reach, especially in rural areas where the business case mandates a maximal coverage.

Band	Freq. Range	Bandwidth	Max. transmit power	Max. EIRP
U-NII-1	5.15 – 5.25 GHz	100 MHz	50 mW	200 W
U-NII-2A	5.25 – 5.35 GHz	100 MHz	250 mW	1 W
U-NII-2B	5.35 – 5.47 GHz	120 MHz	Not used in unlicensed access	
U-NII-2 extended (*)	5.47 – 5.725 GHz	255 MHz	250 mW	
U-NII-3	5.725 – 5.85 GHz	125 MHz	1 W	4 W

Source: Mobile Experts

Figure 3. 5 GHz unlicensed U-NII band ranges

6 GHz

Wi-Fi proponents including Qualcomm, Broadcom, Cisco, WISPs, and others are proposing to have the 6 GHz (5925 – 7125 MHz) band to be "opened up" for unlicensed use, similar to the adjacent 5 GHz band used for Wi-Fi. The band is primarily used by "Fixed Service" and "Fixed Satellite Service" earth station uplink services today in addition to some mobile services (i.e., BAS, CARS, LTTS, and OFS) in certain portions of the band. The proponents argue that the Fixed Service operations are high-power, highly directional, outdoor applications which can be well coordinated with mostly indoor Wi-Fi operations at lower output power. The group is proposing to segment the 6 GHz band (in a similar manner to the 5 GHz band) into multiple U-NII bands as follows in order to protect specific incumbent users of the band.

Note that IEEE has "decided" that only Wi-Fi 6 can be used in the 6 GHz bands. We believe that this decision may hold for other forms of Wi-Fi, but the IEEE cannot stop carriers from using the 6 GHz band with LTE or 5G NR waveforms.

Band	Freq. Range	Bandwidth	Incumbent use	Max. EIRP
U-NII-5	5.925 – 6.425 GHz	500 MHz	Fixed Satellite uplink	??
U-NII-6	6.425 – 6.525 GHz	100 MHz	Mobile BAS, CARS, LTTS, OFS	??
U-NII-7	6.525 – 6.875 GHz	350 MHz	Not used in unlicensed access	??
U-NII-8	6.875 – 7.125 GHz	250 MHz	Mobile BAS, CARS	??

Source: Mobile Experts

Figure 4. Proposed 6 GHz unlicensed U-NII band ranges

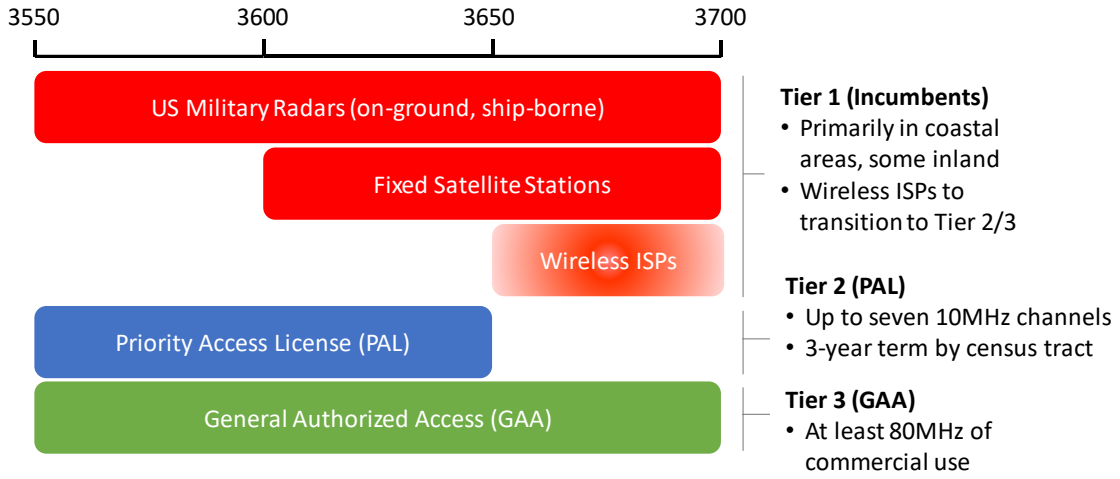
60 GHz UNLICENSED

The 60 GHz unlicensed band provides a tremendous amount of spectrum bandwidth – 14 GHz! With a high oxygen attenuation in the 60 GHz band, the use of this band for fixed wireless is confined to short-reach distances, less than 300 meters. While this band has been used in point-to-point (PtP) context for many years, many vendors are developing point-to-multipoint (PtMP) systems to take advantage of the large swath of spectrum for high-speed broadband access in urban and suburban settings. Many vendors, including Nokia, Siklu, Intracom and others, provide PtMP solutions operating in the 60 GHz band.

Because of high attenuation and short reach, the 60 GHz PtMP solutions will require outdoor antenna deployment and high-gain beamforming capability to enable fast installation and activation. The industry push into the millimeter wave bands as a part of the 5G transition has enlarged the 60 GHz ecosystem and has expanded the market opportunity in the 60 GHz space including the fixed wireless application.

CBRS - Opening New Bands under Shared Spectrum Rules

Considering that a major US mobile operator holds, on average, roughly 130 MHz of licensed spectrum, the 150 MHz of new spectrum in the 3.5 GHz CBRS band is a significant amount of spectrum for further mobile capacity expansion. In addition, the flexible three-tier licensing framework is expected to lower the barrier and promote success-based investments by new entrants. (Please see the below section on CBRS for the details on how the three-tier licensing works.)



Source: Mobile Experts

Figure 5. CBRS Three-Tier (Shared Spectrum) Licensing Structure

The innovative three-tier licensing structure of CBRS opens up new use cases; and, encourages business innovations from traditional operators and new entrants alike. Here is a list of possible opportunities that CBRS can enable for the different stakeholders:

1) Mobile operators can leverage CBRS band as a secondary carrier in LAA deployment to augment network capacity and boost user throughput speed;
2) Cable operators can build LTE networks and leverage that capacity in their MVNO business to minimize or offset MVNO rent costs;
3) Neutral host providers can use CBRS band to stand up LTE networks for in-building wireless services directly to enterprises or to mobile operators for resell;
4) Enterprises can build "private LTE" networks on the CBRS band under GAA or PAL basis with the assumption that PAL licensing costs are not too exorbitant.

The novel three-tier licensing approach encourages the stakeholders to pursue those business opportunities as highlighted above without the burden of high upfront costs for traditional licensed spectrum. Stakeholders will be able to purchase PAL licenses to secure an appropriate amount of spectrum at specific geographic locations to offer wireless services. This type of success-based investment in PAL spectrum licensing attempts to allow efficient use of the band.

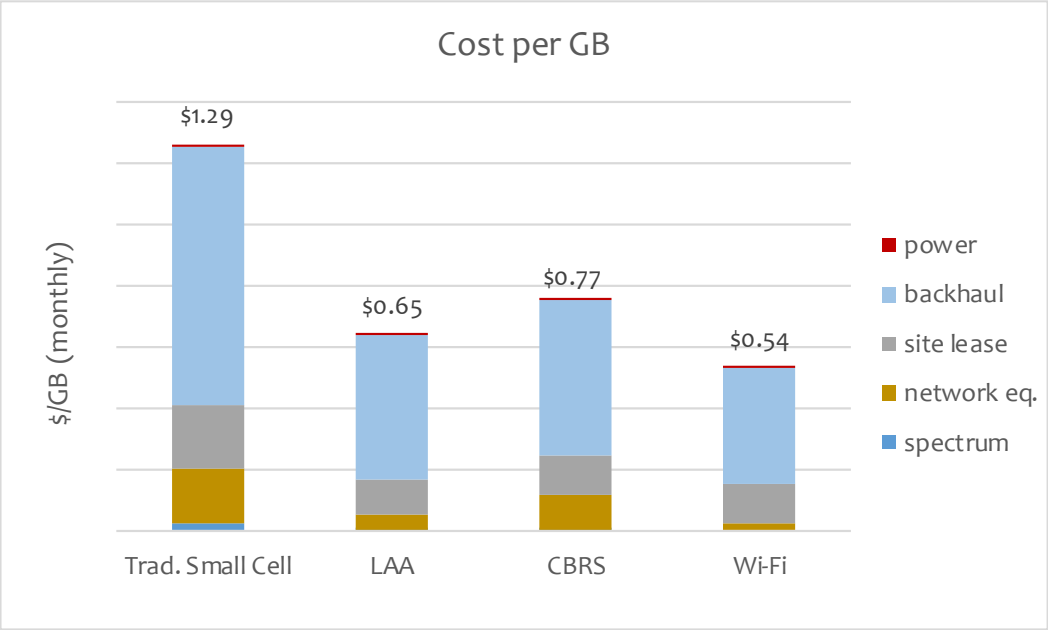
There is some discussion about spectrum sharing in the UK.[2] While it is still uncertain as to whether the three-tier CBRS licensing scheme would be adopted in the UK and EU as a whole, but the fact that Ofcom is discussing the possibility of dynamic spectrum sharing is an encouraging sign that perhaps CBRS rule, or a similar coordinated sharing method, would be adopted in the UK, and perhaps EU in general. While this possibility exists, our forecast does not account for this in the CBRS forecast.

Cost per GB for Unlicensed Options

In last year's report we provided extremely detailed cost analysis to illustrate the choices between Carrier Wi-Fi, LTE-U, LAA, and CBRS. (Refer to MEXP-UNLIC-18). Our view has not changed much, so we won't repeat the full cost analysis here.

In summary, unlicensed options can cut the cost per GB by about half, and operators are strongly motivated to use LAA and CBRS as these two options offer the best compromise of low cost and high quality, compared with the cheaper Carrier Wi-Fi format.

[2] Ofcom spectrum sharing framework:
https://www.ofcom.org.uk/__data/assets/pdf_file/0028/68239/statement.pdf



Source: Mobile Experts

Figure 6. Comparative Cost per GB of LAA vs. CBRS vs. Wi-Fi (Mobile operator costs)

The cost comparison varies between mobile operators, cable operators, and OTT players. We see more adoption of Wi-Fi by cable and OTT players for cost reasons, but also because these players don't have access to licensed spectrum on a nationwide basis that would enable LAA. We may see cable players or OTT players (like Google) participate in the PAL auction or buy spectrum from DISH to get into the licensed LTE game… but so far this has not been the case.

3 TECHNOLOGY OPTIONS

The technology option for carrier unlicensed radio has expanded beyond the traditional IEEE 802.11 roadmap and Wi-Fi ecosystem and now includes LTE-based alternatives:

1) *License-Assisted Access (LAA)* – a 3GPP Release 13 standard that essentially formalizes LTE-Unlicensed (downlink carrier aggregation). Unlike LTE-U, fair coexistence with Wi-Fi in the unlicensed spectrum is handled by listen-before-talk (LBT) capability to ensure that channels are clear before transmission;
2) *Citizen Broadband Radio Service (CBRS)* – a three-tier licensing regime that allows operators to use 150MHz of the 3.5 GHz band in the U.S. on a shared basis. The CBRS channels can be aggregated along with a licensed anchor in LAA fashion or can run LTE-TDD on a standalone basis;
3) *MulteFire* -- running standalone LTE on unlicensed (or shared) spectrum without aggregating unlicensed carrier with a licensed carrier; and,
4) *LTE-WiFi Aggregation (LWA)* -- a 3GPP Release 13 standard that aggregates channel carriers at PDCP layer for downlink. LTE eNodeB base station decides which bearers (Wi-Fi and LTE) to use.

Meanwhile, the Wi-Fi based ecosystem of IEEE 802.11 technology roadmap in concert with commercialization efforts of the Wi-Fi Alliance continue to make great strides in advancing their cause:

1) *802.11 ax* – next-generation Wi-Fi technology that refreshes both the 2.4 GHz and 5 GHz bands with OFDMA and 8x8 MU-MIMO for better efficiency in dense environment;
2) *802.11 ad/ay* – 60 GHz WiGig technology providing multi-gigabit throughput in dense urban environments

802.11ac and 802.11ax (Wi-Fi Connectivity on 2.4 and 5 GHz)

The next-generation, 802.11ax, promises to greatly improve efficiency for high-density connectivity. In other words, it promises higher capacity and more connections in dense environments. The net performance improvement translates to 4x increase in capacity compared to 802.11ac and improved coverage. The higher efficiency is achieved from a few key features found in 802.11ax:

- 8x8 MU-MIMO on both the 2.4 and 5 GHz bands – increase capacity
- OFDMA – improves network efficiency and reduces latency
- Scheduled access
- WPA3 security

A comparison of technical feature sets between 802.11ac and 802.11ax is shown below.

	802.11ac	802.11ax
Frequency bands	5GHz	2.4GHz and 5GHz
Channel sizes	20, 40, 80, 160 MHz	20, 40, 80, 160 MHz
FFT sizes	64, 128, 256, 512	256, 512, 1024, 2048 (four times larger)
Subcarrier spacing	312.5KHz	78.125 kHz (four times narrower)
OFDM symbol duration	3.2 usec + 0.8/0.4 usec cyclic prefix	12.8 usec + 0.8/1.6/3.2 usec cyclic prefix (four times longer)
Modulation (highest)	256 QAM	1024 QAM
Data rates (peak)	433 Mbps (80MHz channel bandwidth, 1 spatial stream)	600 Mbps (80MHz channel bandwidth, 1 spatial stream)
	6.9 Gbps (160MHz channel bandwidth, 8 spatial streams)	9.6 Gbps (160MHz channel bandwidth, 8 spatial streams)

Source: Mobile Experts, National Instruments

Figure 7. Comparison of 802.11ac vs. 802.11ax

As noted above, 802.11ax operates in both 2.4 and 5GHz bands. More importantly, it significantly increases the number of subcarriers while preserving the existing channel bandwidth. Larger OFDM FFT sizes, narrower subcarrier spacing, and longer symbol time, in aggregate, improves robustness and efficiency while keeping the data rates the same as 802.11ac. In fact, with a higher modulation support for 1024 QAM, the 802.11ax provides a higher maximum data rate. More importantly though, it provides higher efficiency in multipath fading environments. With the higher number of subcarriers, the 802.11ax can more efficiently support simultaneous client devices by effectively divvying up the frequency.

Like 802.11ac, 802.11ax devices use explicit beamforming to direct data packets simultaneously to multiple users who are spatially separated. While the 802.11ac only defined MU-MIMO on the downlink, the 802.11ax standard defines uplink multiuser mode as well in which simultaneous data transmission from multiple client devices to an access point is possible. Another key addition of the 802.11ax standard is that it has defined two different ways of multiplexing users: Multiuser MIMO (MU-MIMO) and Multiuser Orthogonal Frequency Division Multiple Access (MU-OFDMA). In essence, 802.11ax borrows the underlying OFDMA technology used in LTE base stations to centrally manage multiple client devices, thus enabling more efficient access to a radio channel.

MU-MIMO operation in 802.11ax is essentially the same as the 802.11ac, in which an access point calculates a channel matrix for each user and steer simultaneous beams to different users with each beam containing specific packets for the intended client user. In 802.11ax, a maximum number of MU-MIMO transmissions has been increased from four to eight. For the uplink MU-MIMO, the access point initiates a simultaneous uplink transmission from each of the client devices by a trigger frame. In the case of multiple client devices responding in unison, the access point applies the channel matrix to the received beams and separates the information from each uplink beams.

In MU-OFDMA operation, specific sets of subcarriers can be allocated to different users over time. In fact, this is the same scheme that LTE uses in allocation of physical resource blocks for multiple users. Borrowing a similar LTE terminology, the 802.11ax defines the smallest subchannel as a Resource Unit (RU), with a minimum size of 26 subcarriers. As noted in the figure below, an access point can allocate the entire (20/40/80/160 MHz) channel to only one user at a time as is currently done in 802.11ac, or it can "chop up" the frequency (in RU) and allocate specific sets of RUs to different users over time.

Also, the resource scheduling in the uplink increases efficiency by moving away from contention-based resource allocation found in 802.11ac to scheduling approach (like LTE). With a combination of downlink and uplink MU-MIMO and MU-OFDMA, the 802.11ax is expected to support four times the average user throughput. With combinations of these techniques and higher physical data rates, 802.11ax is expected to improve user throughput and extend coverage with higher 8x8 MIMO, especially in dense environments, which has been an Achilles' Heel for Wi-Fi relative to LTE. Note that the MU-OFDMA and resource scheduling will improve contention between clients that share an access point, but not for users on different access points.

802.11 ad/ay (on 60 GHz)

The 60 GHz unlicensed technology widely known as 802.11ad WiGig has been around for many years. After the WiGig Alliance merged into the Wi-Fi Alliance back in early 2013, 802.11ad WiGig technology has been positioned as a "multi-gigabit Wi-Fi" technology for short-range applications such as wireless connectivity for VR headsets, HDMI/USB replacement, and so on. In the carrier space, 60 GHz 802.11 ad/ay solutions are sometimes found in short-range (100 meter) wireless backhaul applications.

The Facebook's Terragraph open-source project is the latest incarnation of ecosystem "builder" looking to rally other key companies to create fiber-replacement technology solution for multi-gigabit wireless connectivity solution for urban areas. Qualcomm is a major 60 GHz chipset supplier along with Intel and Peraso in this space. Qualcomm has already announced its pre-802.11ay chipset, and we are aware of many 60 GHz radio vendors looking to exploit the fixed wireless space with the 60 GHz point-to-multipoint radio solutions.

Source: Facebook Terragraph

Figure 8. Facebook Terragraph 60 GHz PtMP Network Architecture View

A key benefit of 60 GHz spectrum is the ultrawide channel – 2.16 GHz channel spacing! A whole lot can be transmitted in that amount of spectrum. Local regulatory bodies determine regional spectrum allocation from the total of six channels:

- USA: 57.0 – 71.0 GHz (6 channels available)
- Europe: 57.0 – 66.0 GHz (2 channels available)
- China: 59.0 – 64.0 GHz (2 channels available)
- S. Korea: 57.0 – 64.0 GHz (3 channels available)
- Japan: 57.0 – 66.0 GHz (4 channels available)
- Australia: 59.4 – 62.9 GHz (just shy of 2 channels available)

Due to the physical limits of RF propagation at the 60 GHz band, a range is fairly short – typically 200 meters in point-to-point wireless backhaul applications (although we have seen some vendors claiming even longer distances).

802.11ay is the next-generation 60 GHz technology that further extends the transmission speed and range. A draft 1.0 of the 802.11ay specification is expected to be released in the second half of 2017. According to the draft specification, the standard proposes to support 20-30 Gbps transmission rate and extend the range to 300-500 meters. These improvements are expected to be achieved through:

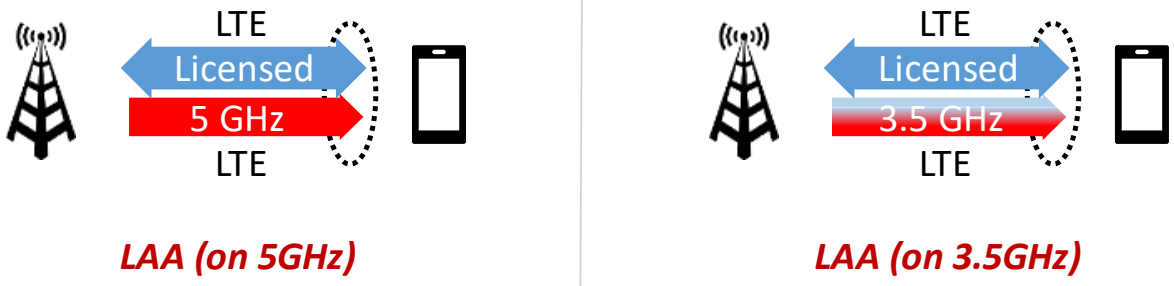
- Up to 4 channel bonding (each 802.11ad channel uses a maximum of 2.16 GHz bandwidth), yielding a maximum bandwidth of 8.64 GHz
- MIMO with a maximum of 4 spatial streams (a link rate per stream is 44 Gbps; thus with 4 streams, this can go up to 176 Gbps)
- High-order modulation scheme, possibly up to 256 QAM

With the tremendous amount of spectrum available in the 60 GHz unlicensed spectrum, 802.11 ad/ay solutions should find a home in many consumer and enterprise applications.

For the carrier space however, it will likely be used only for fixed wireless access and backhaul applications in dense urban environments. For the fixed wireless application, the CPE cost is a major determinant of viable business case. While the ecosystem is making great strides, we believe the market is still about 1-2 years out. The Terragraph ecosystem may provide enough scale and technology advancements to allow the 60 GHz point-to-multipoint market to flourish a bit sooner.

License-Assisted Access (LAA)

License Assisted Access (LAA) is built upon the carrier aggregation framework adopted in LTE Advanced (Release 10 through 13). Carrier aggregation combines more than one channel within the same band or with another band, effectively increasing the overall bandwidth available to a user equipment, thereby increasing bitrate. In the LAA framework, the unlicensed 5 GHz band is considered a secondary cell for downlink while the primary cell connection reserved for control signaling and uplink is anchored to a licensed band thus providing means to control service quality through control signaling on "guaranteed" licensed anchor carrier.



Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) Dotted ellipse represents that licensed/unlicensed/shared spectrum carriers are aggregated at the UE client device;

Source: Mobile Experts

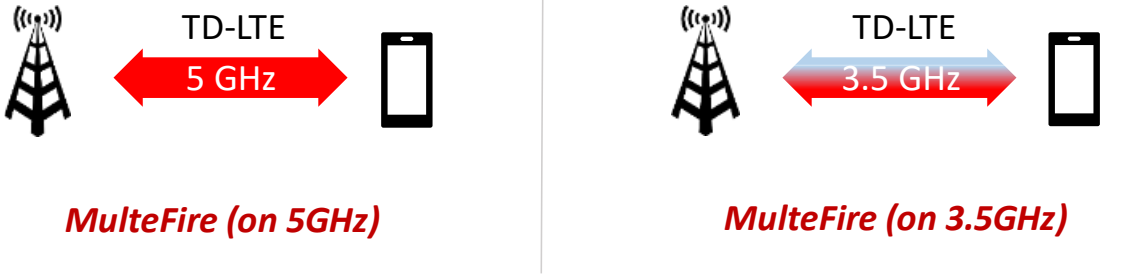
Figure 9. LAA Functional Overview

While the early head start that Verizon and T-Mobile were pushing for in the USA with LTE-Unlicensed (LTE-U) specification, a predecessor to LAA, did not materialize, the global scale of standardized LAA is expected to bring large scale as operators with limited spectrum view LAA as a path forward to opportunistically expand network capacity using cheap unlicensed spectrum.

MulteFire (on 3.5 GHz, 5 GHz, and Beyond)

Qualcomm, Nokia, Ericsson, and Intel formed the MulteFire Alliance to push for the unlicensed LTE technology that can be leveraged without a licensed spectrum anchor. In essence, MulteFire is an incarnation of LAA for those operators who do not have licensed spectrum for an "anchor" carrier for primary cell. Unlike LAA which precludes use by those who do not have licensed spectrum, MulteFire proposes to carry both control plane and data plane traffic entirely over unlicensed or shared band in a full TDD mode. Thus, it can be leveraged by enterprises, venue owners, and fixed providers.

Some view MulteFire as "CBRS for the rest of the world" outside of USA. It is still unclear today how much efficiency gain could be had with MulteFire over 802.11ax -- especially in light of the fact that 802.11ax tout 4x average user throughput improvement.[3] LTE standards allow for better coordination between cells than 802.11ax, but this is not proven in MulteFire field networks to date. In theory, the LTE ecosystem can be broadened to fixed operators or enterprises using the unlicensed spectrum.



Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) "Standalone" LTE via MulteFire can run on 5 GHz unlicensed spectrum as well as shared CBRS spectrum on PAL or GAA basis;
4) Multiple carriers on shared CBRS spectrum can be aggregated with licensed anchor carrier in LTE-U/LAA.

Source: Mobile Experts

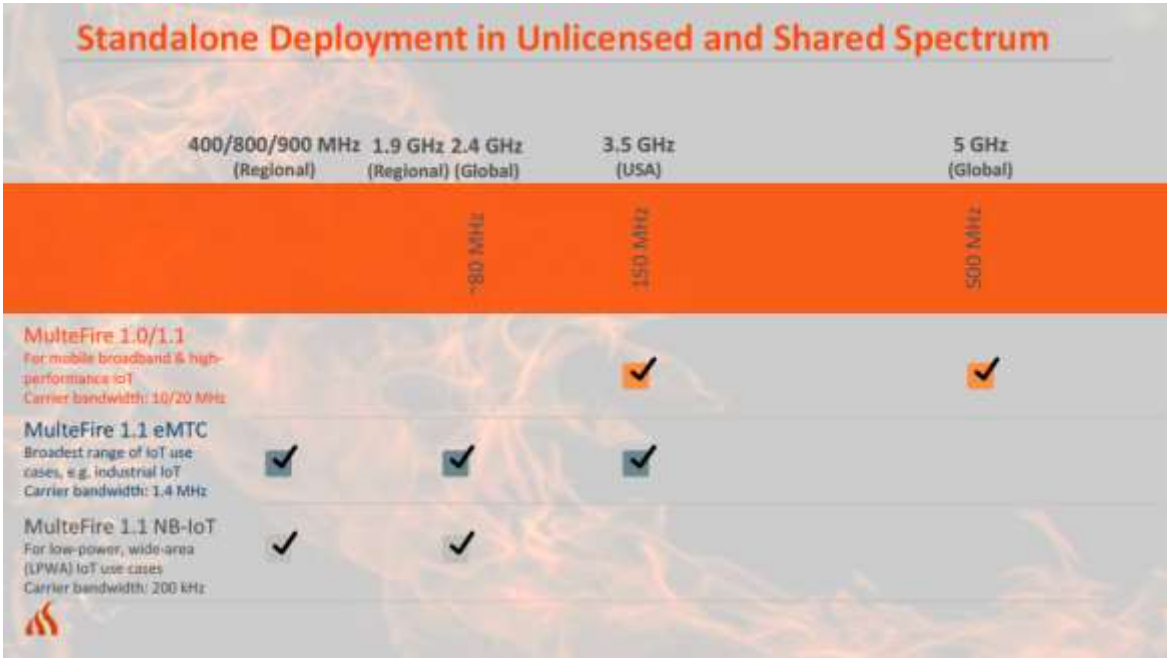
Figure 10. MulteFire Functional Overview

In practice, however, the adoption of MulteFire by the key target audiences, enterprises and operators, remains unclear. Enterprises have a large installed base of Wi-Fi systems and

[3] According to Qualcomm's MulteFire presentation dated May 24, 2016, MulteFire is expected to offer ~2x capacity gain over Wi-Fi (802.11ac). IEEE 802.11ax stated goal is to improve the average user throughput by 4x.

client devices. Though the neutral host and multi-operator aspects of MulteFire are clear demand drivers, whether the MulteFire ecosystem can achieve the competitive equipment pricing and scale of Wi-Fi remains unclear.

One likely area of market adoption of MulteFire may be in 3.5GHz CBRS deployments. Traditional mobile and Wi-Fi infrastructure vendors such as Nokia, Ericsson, Cisco, and Ruckus have joined the MulteFire Alliance. While we remain skeptical of its viability in the 5GHz band, we believe the benefits of MulteFire, namely neutral host support, private LTE applications in the "fresh" 3.5GHz CBRS band. In addition, it may provide a suitable solution for industrial IoT applications that require more deterministic service quality -- guarantees of performance will be more achievable with LTE than with Wi-Fi. As outlined in the MulteFire roadmap below, the ecosystem is expanding for IoT and Private LTE applications and expanding the specification to include other unlicensed spectrum bands as it monitors "5G Unlicensed" use case leveraging wider band possibly in the millimeter wave bands. According to the MulteFire Alliance, the MulteFire 1.1 specification is targeted for mid-2018, and is working towards Certification program.



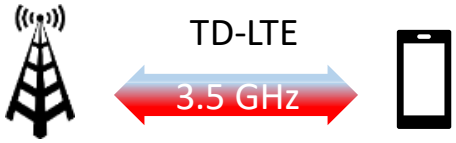
Source: MulteFire Alliance

Figure 11. MulteFire Roadmap Targets Mobile Broadband and IoT

CBRS (on 3.5 GHz)

In 2015, the U.S. Federal Communications Commission (FCC) formally established *Citizen Broadband Radio Service* (CBRS) for shared commercial use of the 3.5 GHz (3550-3700 MHz) band with the incumbent military radars and fixed satellite stations. For the first time, dynamic spectrum sharing rules have been defined to make additional spectrum available

for flexible wireless broadband use while ensuring interference protection and uninterrupted use by the incumbent users. The CBRS rule essentially allows mobile operation in TDD mode under coordinated sharing.



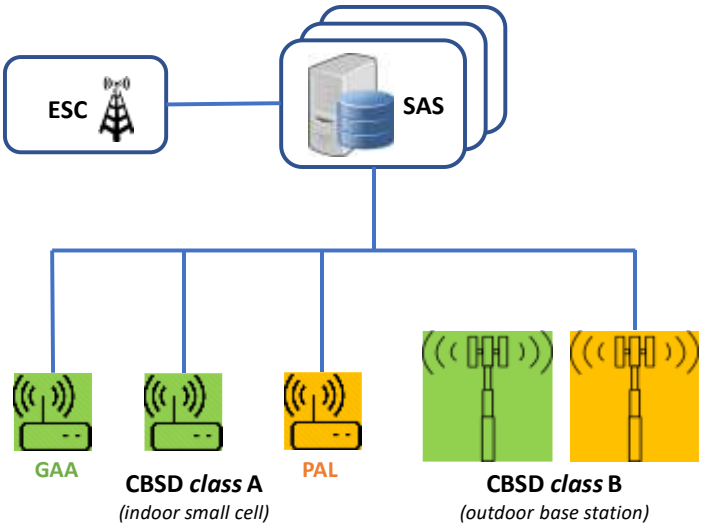
Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) "Standalone" LTE via MulteFire can run on 5 GHz unlicensed spectrum as well as shared CBRS spectrum on PAL or GAA basis;

Source: Mobile Experts

Figure 12. CBRS Conceptual Diagram

Under the plan, a three-tier sharing paradigm coordinates spectrum access among the incumbent military radars and satellite ground stations and new commercial users. The three tiers are: *Incumbent*, *Priority Access License* (PAL), and *General Authorized Access* (GAA) users.

A key element of the CBRS spectrum sharing architecture is the *Spectrum Access System* (SAS). A SAS maintains a database of all CBRS base stations, formally referred to as *Citizens Broadband Radio Service Devices* (CBSDs), including their tier status, geographical location, and other pertinent information to coordinate channel assignments and manage potential interferences. To mitigate possible interference to tier 1 military radar systems, environmental sensors known as the *Environmental Sensing Capability* (ESC) are deployed in strategic locations near naval stations, mostly along coastal regions, to detect incumbent activities. When incumbent use is detected, the ESC alerts the SAS, which then directs CBSDs utilizing impacted CBRS channels in that area to move over to other channels. The cloud-based SAS enforces the three-tier spectrum sharing mechanism based on FCC rules via centralized, dynamic coordination of spectrum channel assignments across all CBRS base stations in a region.



Source: Mobile Experts

Figure 13. CBRS Functional Overview

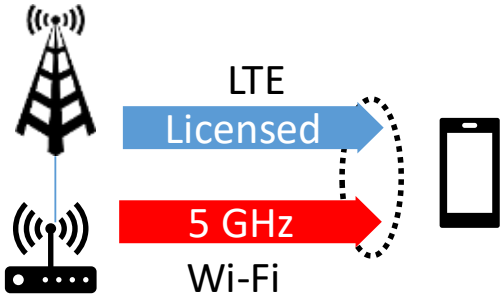
The CBRS rulemaking defines two classes of base stations: *class A* and *class B*. A class A base station can be thought of as indoor or low power outdoor small cells with a maximum conducted power of 24 dBm (per 10 MHz) and maximum EIRP of 30 dBm (1 watt). This type of small cell is similar to "enterprise-class" small cells in the marketplace with 250mW transmit power with a typical 2 dBi omni antenna or up to 6 dBi directional antenna. Meanwhile, a class B base station is meant for outdoor use with a maximum EIRP of 47 dBm (50 watts). With a very high-gain antenna, outdoor CBRS base station can potentially be used for fixed wireless purposes. While indoor and outdoor base stations can be assigned to either GAA or PAL, we expect to see more indoor GAA deployments until ESC certification and PAL auctions get finalized.

In the past year, the CBRS ecosystem was hampered by the delayed FCC certification of SAS. FCC certification of SAS is now ready for market. While there is still uncertainty around the final CBRS rules around spectrum license area size and term duration,[4] we expect CBRS radio deployments under GAA operation to start at the end of 2018 and possibly early 2019. While the expected ramp has been delayed by the government, Mobile Experts believes that CBRS network deployments will scale once the FCC provides clarity with a final ruling and PAL auction – likely in the first half of 2020. Despite remaining uncertainties around final ruling and certification process at the government agencies, commercial rollout for fixed wireless and private LTE applications appears to be close at hand.

[4] CTIA and T-Mobile separately requested CBRS rule changes to FCC: http://www.fiercewireless.com/wireless/t-mobile-joins-ctia-pushing-fcc-to-reform-rules-for-3-5-ghz

LTE WLAN Aggregation (LWA)

LTE WLAN Aggregation (LWA) as defined in 3GPP release 13 provides a method to integrate LTE and Wi-Fi access network. LWA essentially aggregate or switch data traffic over LTE and Wi-Fi airlinks at radio access network layer – PDCP layer to be exact, just below the IP layer. In effect, end users would experience a capacity boost from utilizing Wi-Fi network as if they were using LTE. One of the drawbacks of LWA is that the link aggregation only works on the downlink only and does require changes to WLAN access point infrastructure. Perhaps due to these drawbacks, we have not observed much market traction of this method in commercial deployments beyond limited commercial launch in Taiwan and Singapore.



Notes: 1) Blue arrow represents licensed spectrum; Red represents unlicensed spectrum; Blue/Red gradient represents shared spectrum;
2) Directions in arrows represent downlink or both downlink and uplink operation on specific spectrum type;
3) Dotted ellipse represents that licensed/unlicensed/shared spectrum carriers are aggregated at the UE client device;

Source: Mobile Experts

Figure 14. LWA Functional Overview

4 OVERALL "UNLICENSED" CARRIER NETWORK OUTLOOK

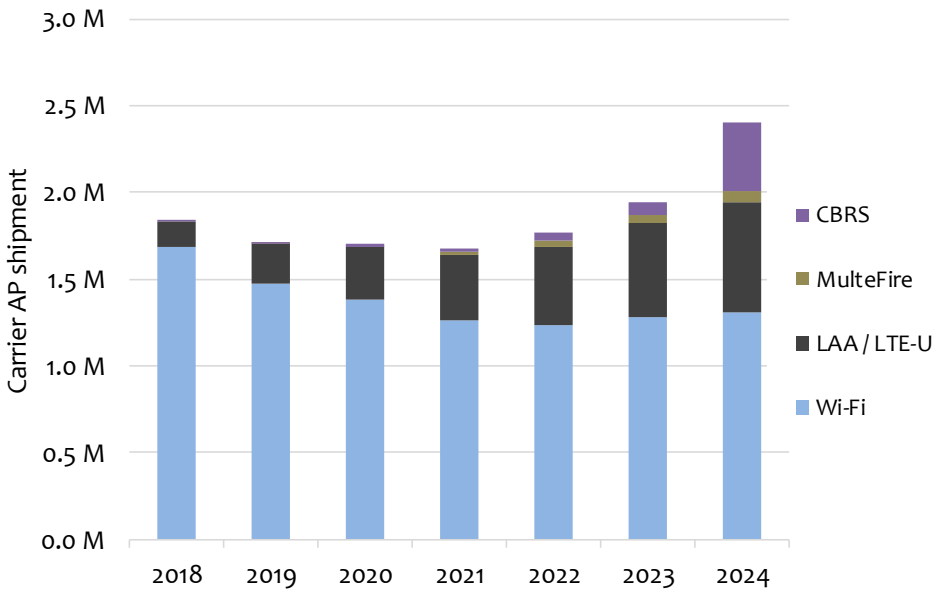
The carrier market for unlicensed radios will grow steadily. The past year has been a "holding pattern" as the CBRS PAL licenses have not been auctioned, but LAA has started and operators have spent the past 12 months working out the details of implementation in multiple bands.

In this report, a carrier "unlicensed" radio node can be deployed as a standalone access point (AP) or integrated into a customer premise equipment (CPE) for broadband at home or business. For example, a standalone AP can be mounted on lampposts for public hotspot coverage or on a tower or rooftop for fixed wireless services. In addition, carriers typically integrate Wi-Fi onto CPEs to extend broadband connectivity service to increasing number of wireless devices at homes and businesses.

Carrier Unlicensed Radio Shipment Forecast

The early days of Carrier Wi-Fi deployments by the mobile operators for data offload are gone. We've been watching Carrier Wi-Fi drop for some time, as LAA aggregation plans and other approaches gain maturity. Overall, the market in unlicensed bands has dropped a bit, as operators are not happy with Wi-Fi, but are not quite ready for the alternatives.

Despite the drop, we have strong faith that shipments of unlicensed radios will find their way into the network. LAA is coming along strong, and the PAL license auction for CBRS will come in early 2020 to spark growing deployment.



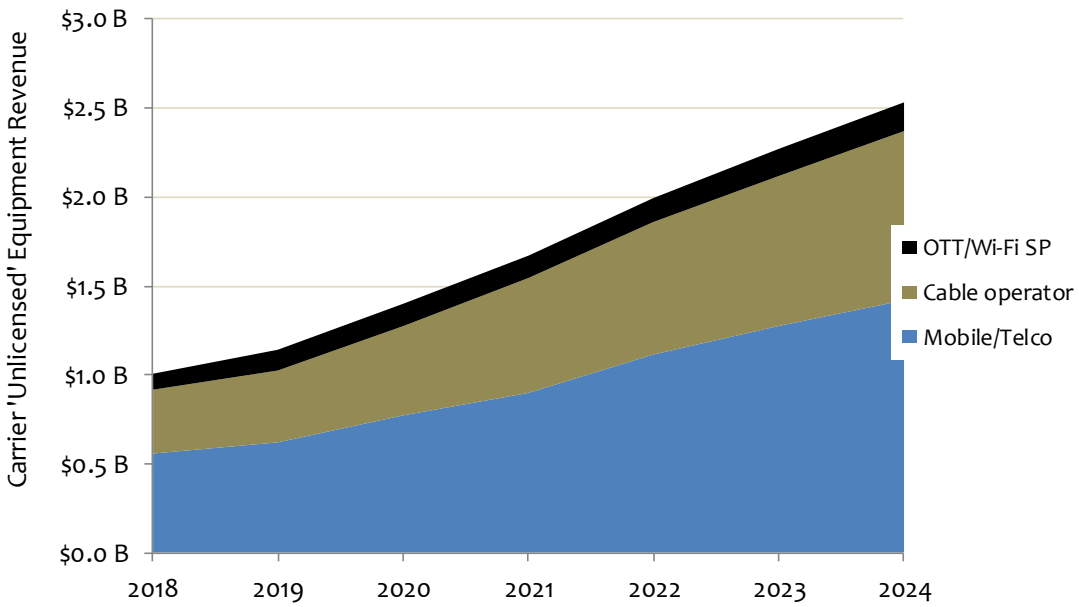
Source: Mobile Experts

Chart 2: Carrier Unlicensed AP Shipment Forecast, 2018-2024

Carrier Unlicensed Radio Revenue Forecast

The revenue for LAA or CBRS access points will be higher than typical Carrier Wi-Fi APs, so we're anticipating steady growth in this market. In particular, we expect to see growing spending in the cable market as the cable operators begin to invest in LTE options and mobile radio solutions.

The primary driver here is capacity: The operators are investing in CBSD units, small cells with LAA, or Carrier Wi-Fi APs to add capacity where the mobile network is overextended. For this reason they are willing to pay

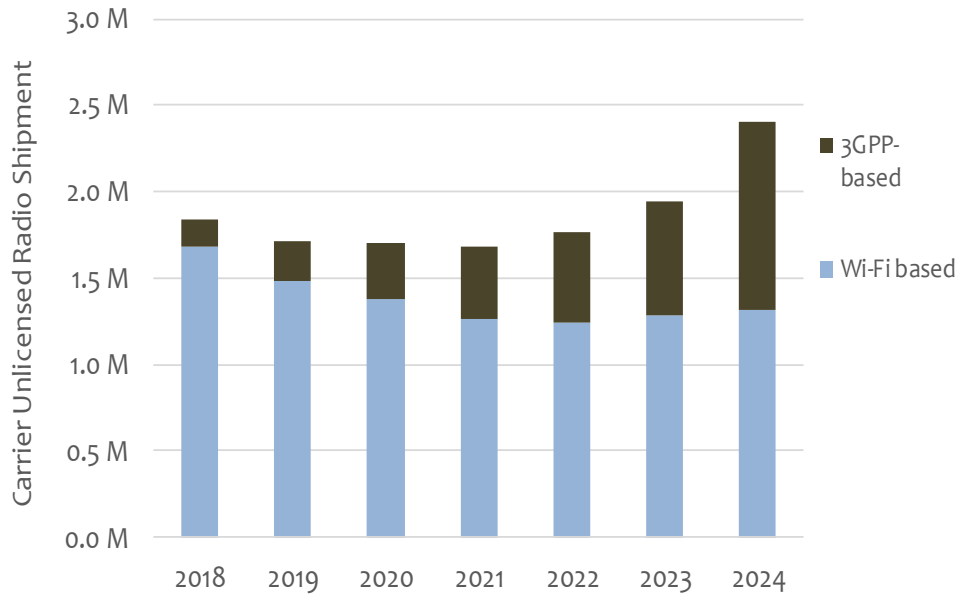


Source: Mobile Experts

Chart 3: Overall Carrier Unlicensed Access Equipment Revenue Forecast, 2018-2024

Carrier Wi-Fi vs. LTE-U and 5G-U

Unlicensed band use by the carriers is clearly shifting from the IEEE-based WI-Fi format to the 3GPP-based LTE format, which of course will be followed by an unlicensed version of the 5G NR standard.

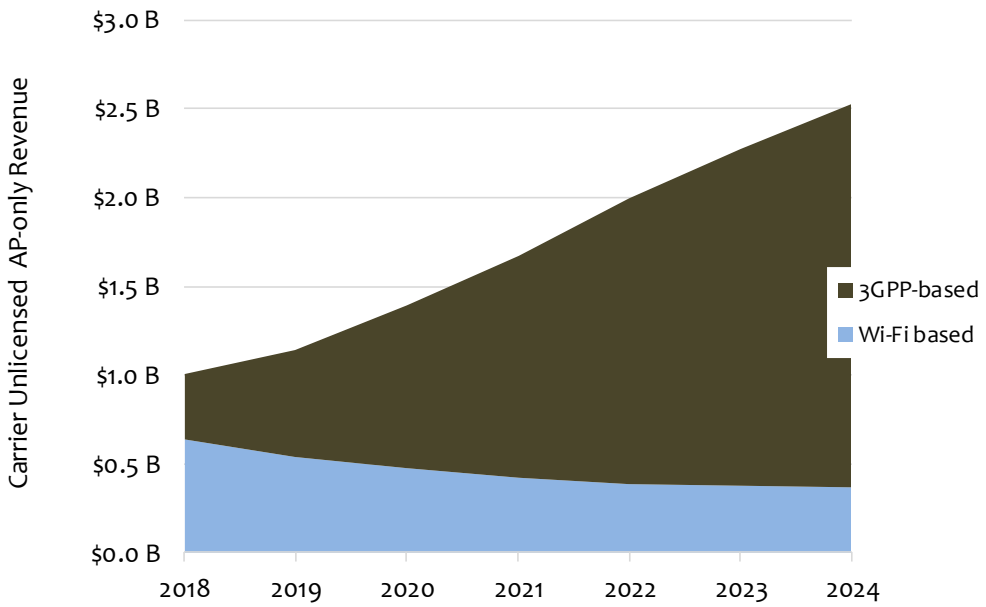


Note: Only captures Wi-Fi integrated broadband CPEs; Excludes video set-top CPEs

Source: Mobile Experts

Chart 4: Carrier Unlicensed Radio Shipment Forecast, Wi-Fi vs. LTE/ 5G, 2018-2024

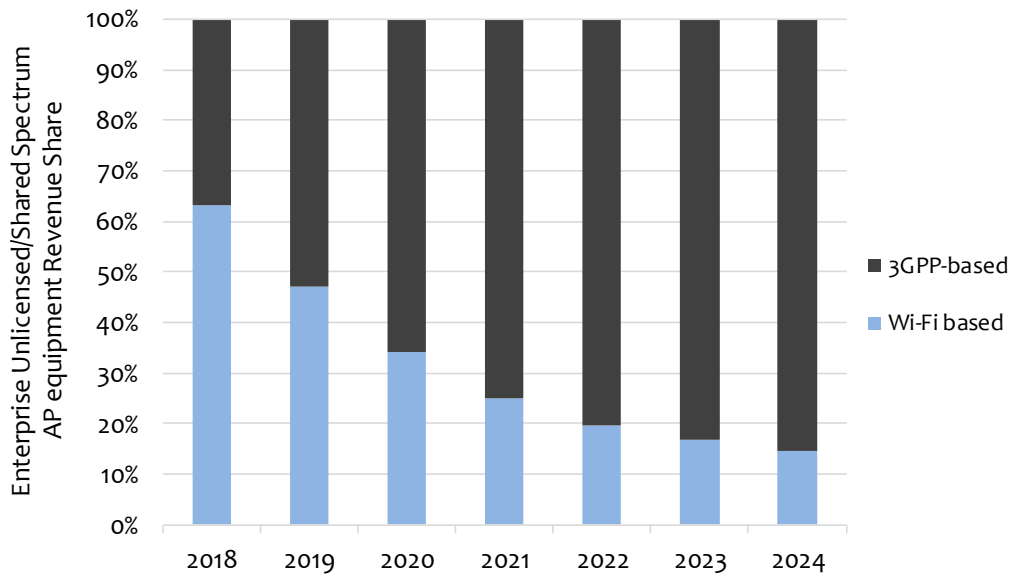
The various solutions in the "3GPP" category include LWA, LAA, LTE-U (without an anchor licensed band), CBRS, and 5G versions of all of the above. While Carrier Wi-Fi is pretty simple, the LTE and 5G options will depend on what other coverage is available for the carrier. Mobile operators prefer LAA, using a strong licensed band as an anchor. Cable operators prefer unlicensed options and are looking at CBRS as a primary LTE coverage band currently. Mobile Experts forecasts this group of LTE-based technologies to represent over $2 billion in Carrier Unlicensed Radio infrastructure equipment revenue by 2024. With higher unit volume shipment, but lower average selling price, the Carrier Wi-Fi equipment market is expected to decline to about $300M in 2024, as the majority of mobile operator spend on "unlicensed" infrastructure moves to LAA and CBRS.



Source: Mobile Experts

Chart 5: Carrier Unlicensed Radio Equipment Revenue Forecast, Wi-Fi vs. 3GPP, 2018-2024

The 3GPP-based unlicensed investment will grow quickly, as new options such as LAA and CBRS come to market in a meaningful way during 2019 to 2021. The 3GPP segment is expected to increase market share capture of the overall Carrier Unlicensed Radio equipment market – growing from just over 20% in 2017 to over 85% in 2024. market representing over $9B by 2023. That is a meaningful impact when one considers that the LTE-based access market represented only 2% of the total carrier unlicensed radio equipment revenue in 2017.

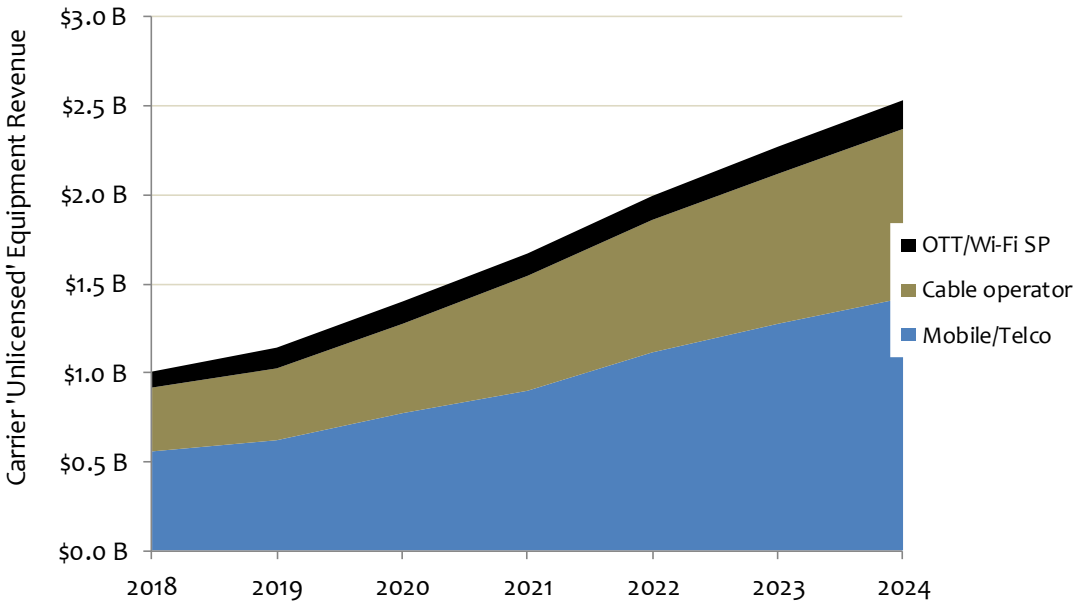


Source: Mobile Experts

Chart 6: Carrier Unlicensed Radio Equipment Revenue Share, Wi-Fi vs. 3GPP, 2018-2024

Carrier Unlicensed Radio Outlook by Operator Type

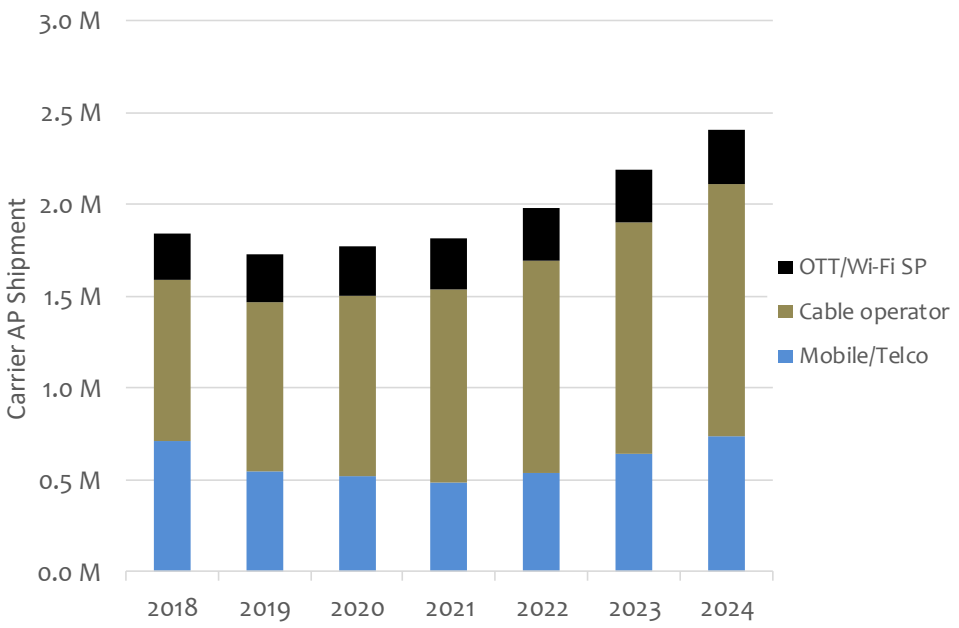
All types of communications service providers (CSPs) are expected to grow their investments in the unlicensed bands. The mobile operators represent the biggest purchasers of carrier unlicensed wireless infrastructure equipment such as Carrier Wi-Fi and Wi-Fi integrated broadband CPEs today, and should remain the leading spenders. Cable operators come in second, with strong expected growth with CBRS, then the OTT/WiFi operators (such as Boingo, Google, and others) round out the field.



Source: Mobile Experts

Chart 7: Carrier Unlicensed Radio AP Equipment Revenue by Operator Segment, 2018-2024

At a shipment level, we see that mobile operators are currently deploying the highest number of radio nodes, but cable operators are likely to deploy higher numbers of low-cost radio nodes over the next few years. Cable operators have access to strand-mount locations, so they will be able to deploy large numbers of small cells quickly.



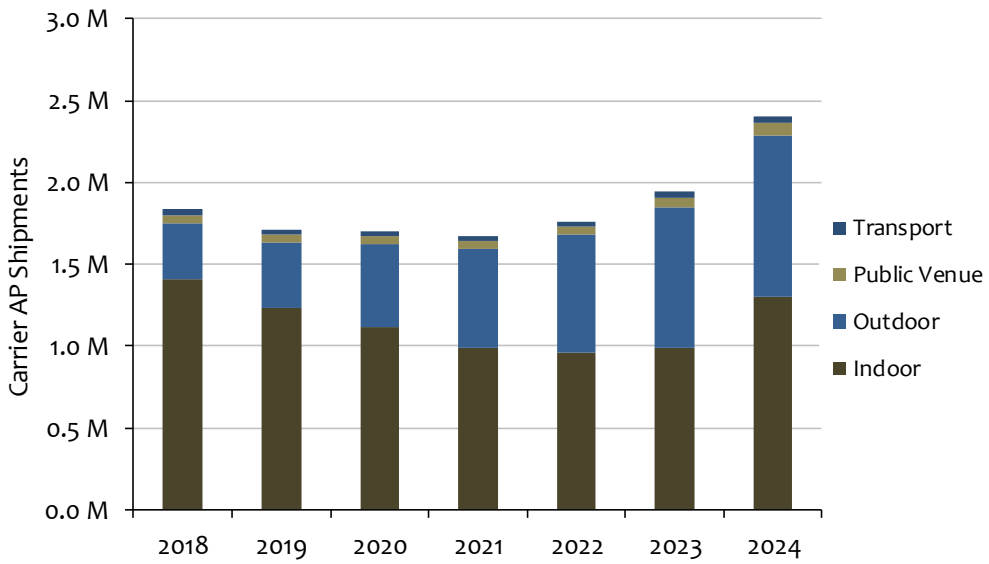
Source: Mobile Experts

Chart 8: Carrier Unlicensed AP Shipment Forecast by Service Provider, 2018-2024

Carrier Unlicensed Radio Indoor vs Outdoor Outlook

Most Carrier Unlicensed Radios are deployed indoors today, but we expect to see significant deployment of LAA and CBRS in outdoor locations. The strand-mounted CBRS small cell and the streetlight-mounted LAA/LTE small cell will be two great examples of the move toward outdoor locations.

Carrier Wi-Fi deployments at key public venues like stadiums and airports will continue, as it's hard to change the public's perception of the value of "Free Wi-Fi". Also, with regard to "transport" applications such as trains and planes, we expect Carrier Wi-Fi to remain the preferred approach for a long time.



Note: Only captures Wi-Fi integrated broadband CPEs; Excludes video set-top CPEs

Source: Mobile Experts

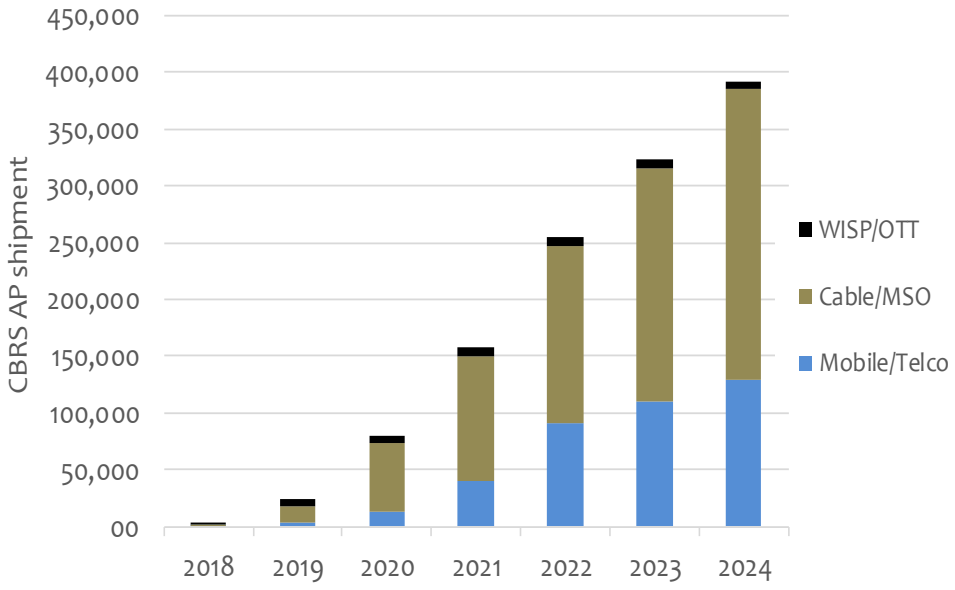
Chart 9: Carrier & Enterprise Unlicensed Radio Shipment, by Market Segment, 2018-2024

5 CARRIER WI-FI OUTLOOK

Unlicensed spectrum has been practically synonymous with Wi-Fi for the past 10+ years, and public Wi-Fi deployment has gone through multiple cycles of boom and decline. In general, mobile operators have tried Wi-Fi and have moved on, with a preference for 3GPP based technologies with more robust scheduling.

Wi-Fi 6 (802.11ax) holds some promise for fixing the perceived problems with contention, as .ax includes OFDM and a scheduling feature which helps in cases where all APs are controlled together. Enterprise wireless local area networking (WLAN) applications and public Wi-Fi in controlled venues will continue to enhance Wi-Fi performance and capacity in this way, but we expect the carriers to continue their migration toward LTE and eventually 5G.

Cable operators will migrate more slowly than the mobile operators in general, if simply because of institutional inertia (companies that rely on Wi-Fi as a core service cannot have a 'religion' against Wi-Fi, as we see in the case of mobile operators). The other over-the-top service providers like wireless ISPs (WISPs) will continue to rely on Wi-Fi based AP infrastructure for data offload and location-based services. Excluding the mobile operators, carriers will continue to look to Wi-Fi technology to harness the unlicensed spectrum bands especially as possible new spectrum in the 6GHz band and 60 GHz product solutions become more widely available.

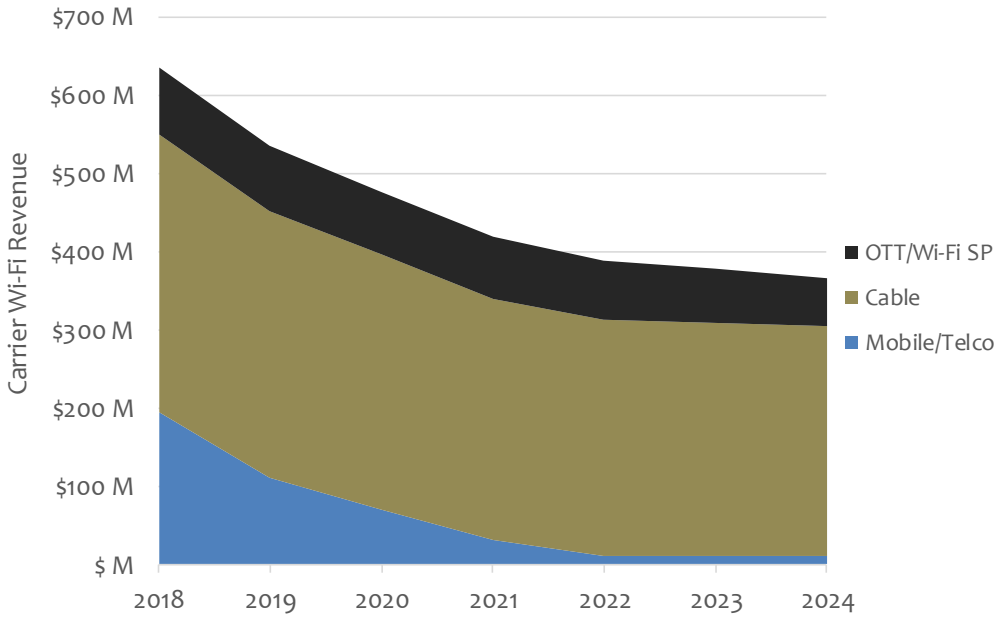


Source: Mobile Experts

Chart 10: Carrier Wi-Fi (standalone) AP Shipments by Operator Segment, 2018-2024

Carrier Wi-Fi Revenue Forecast

With the decline in Carrier Wi-Fi shipments overall, we expect steadily declining revenue for the infrastructure. The mobile segment will decline most quickly, and overall we anticipate hat the market will drop by more than 30% by 2024.



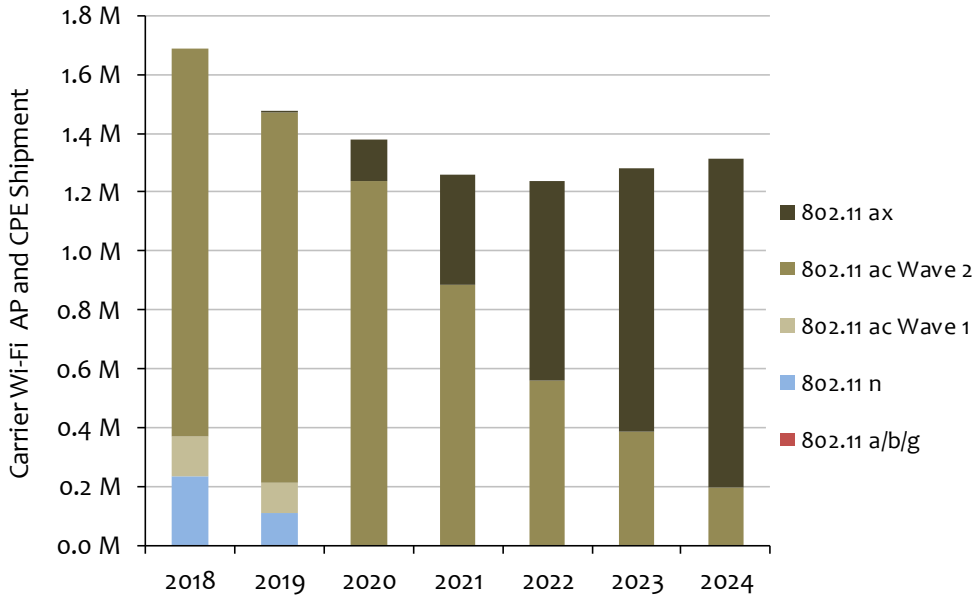
Source: Mobile Experts

Chart 11: Carrier Wi-Fi Equipment Revenue by Operator Segment, 2018-2024

Carrier Wi-Fi 802.11 Technology Transition

The IEEE 802.11 technology transition in the Carrier Wi-Fi segment had historically trailed that of the Retail or Enterprise WLAN market segments. Generally, the Retail/SOHO and Enterprise markets adopt newer 802.11 technology, followed by the Service Provider or Carrier segment. While the IEEE 802.11ax draft approval has been delayed, we still expect 802.11ax enterprise WLAN products to hit the market in second half of 2019, with adoption in handsets throughout 2020 and beyond. The Carrier Wi-Fi products supporting 802.11ax to hit the market in 2020 and go 'mainstream' thereafter.

To take advantage of OFDMA and 8x8 MIMO features that provide performance improvements including "scheduled access" benefits, we expect some operators to adopt 802.11ax faster than historical trends. For example, Comcast is already deploying 8x8 MIMO feature on its 802.11ac Wi-Fi integrated CPE products as a part of its xFi service launch. While the Comcast's xFi CPE is not officially 802.11ax, the core feature of 8x8 MU-MIMO feature provides the benefits early on while the Wi-Fi chipset ecosystem works towards commercializing the official 802.11ax products to the market.



Note: Only captures Wi-Fi integrated broadband CPEs; Excludes video set-top CPEs

Source: Mobile Experts

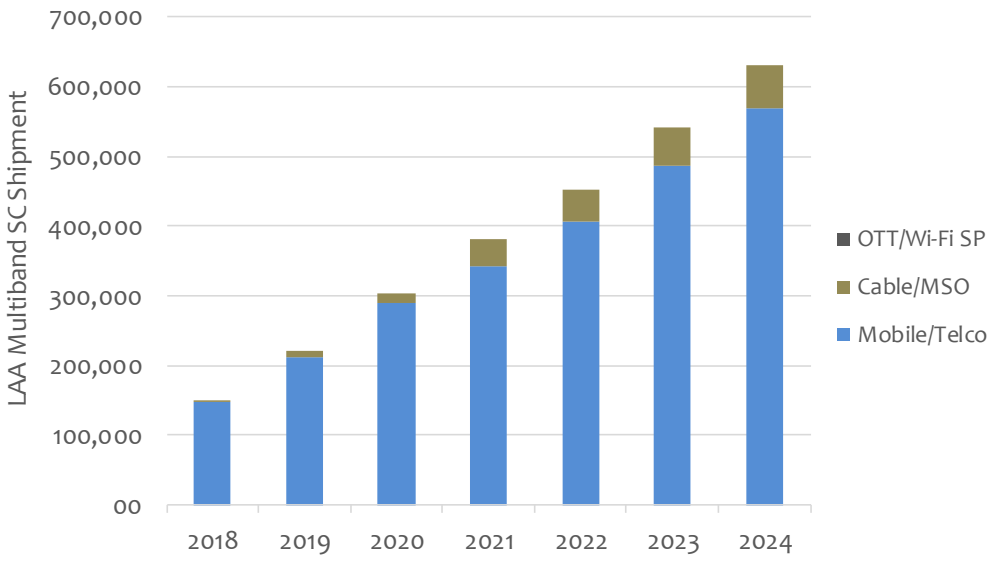
Chart 12: Carrier Wi-Fi 802.11 Technology Transition, Wireless Access Market, 2018-2024

6 "3GPP-UNLICENSED" (LAA, CBRS, LTE-U, 5G-U) OUTLOOK

Deployment of unlicensed radios will add incrementally to the mobile telco infrastructure market. Almost all mobile telcos worldwide have a need to boost capacity, and options such as LAA can offer the cheapest possible way for them to augment their existing networks.

LAA Shipment Forecast

Mobile Experts expects LAA to be the primary method for adding unlicensed capacity below 6 GHz. The licensed-assisted manner in LAA allows the mobile operators to effectively leverage the unlicensed "public" spectrum for its "private" use by managing service quality through control signaling on licensed anchor band, which is, by definition, exclusive to a mobile operator. Mobile Experts expects the mobile operators to opportunistically leverage the unlicensed 5 GHz band in the near term, and the 3.5 GHz CBRS band, under PAL license, to increase capacity. At 5 GHz, this type of deployment is already well underway.



Note: includes predecessor LTE-U units

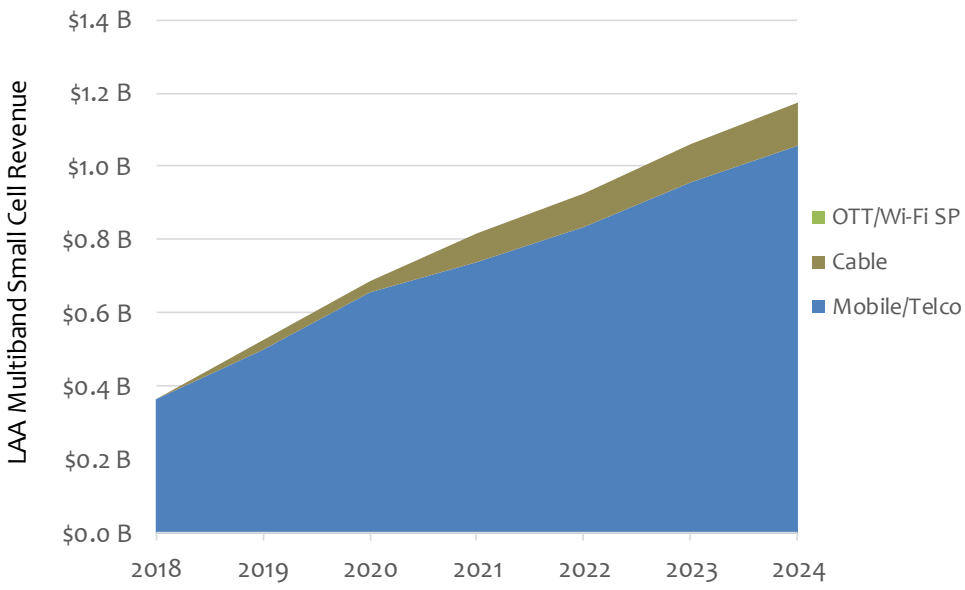
Source: Mobile Experts

Chart 13: LAA Shipment Forecast by Operator Segment, 2018-2024

There is a possibility that cable operators may also deploy LAA with licensed or CBRS PAL spectrum to augment mobile network capacity on its own facilities-based network. There is a lot of uncertainty around this prospect, but we have denoted this possibility in our forecast starting 2020-- in anticipation of the CBRS PAL auction taking place in the first half of 2020.

LAA Revenue Forecast

LAA represents the strongest growth prospect in the Unlicensed segment – from just under $400M in 2018 to about $1.2 B in 2024. Because of the nature of reliance upon licensed spectrum for the "anchor" carrier, LAA is mainly reserved for the mobile operators. However, we expect the U.S. cable operators to participate as well, using the 3.5 GHz shared spectrum as the anchor carrier and leverage LAA for the additional spectrum access to deepen its mobile network capacity. In the end, LAA will be most appealing to the mobile operators with limited spectrum holdings, and the mobile operators will be the primary beneficiaries of this technology.

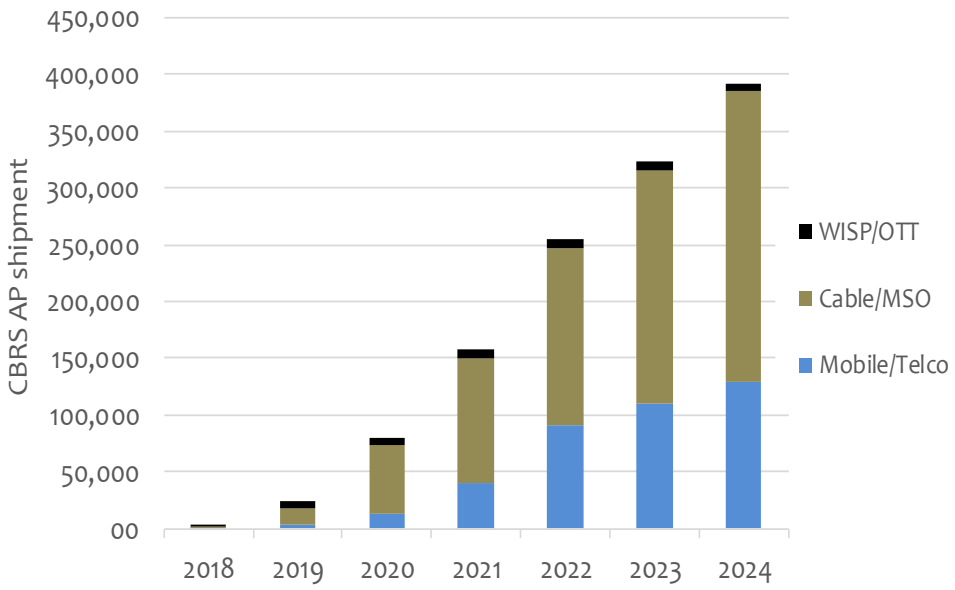


Source: Mobile Experts

Chart 14: LAA Equipment Revenue by Operator Segment, 2018-2024

CBRS Shipment Forecast

The CBRS ecosystem has been coming together over the past three years, and most aspects are now well proven. It's a complex ecosystem that needs to work together, with sensing networks and SAS control, but the trials during 2019 have proven that it all works, and we expect commercial deployment in 2020 to take off in earnest.



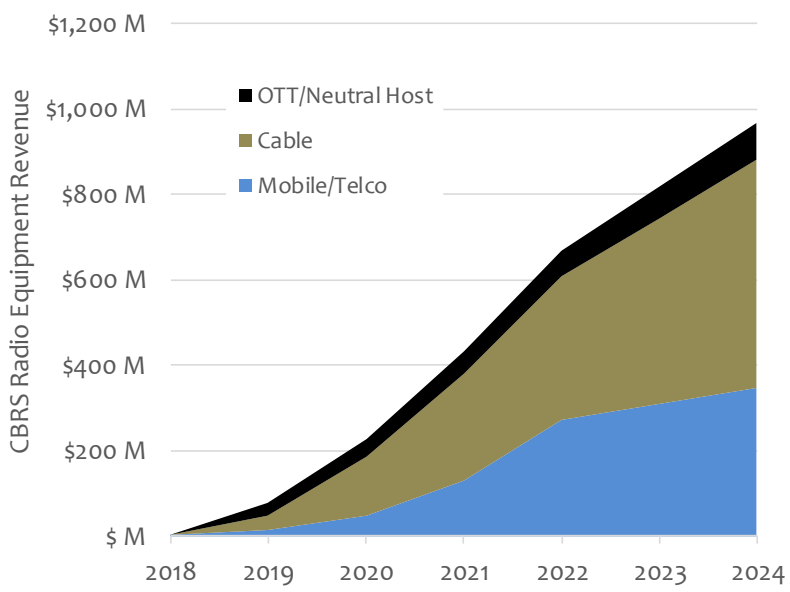
Note: Excludes AP units related to fixed wireless access application

Source: Mobile Experts

Chart 15: Carrier CBRS AP Shipment Forecast, 2018-2024

CBRS Revenue Forecast

There's a diverse set of customers for CBRS and of course that means a diverse set of products for different applications. Mobile and cable operators will use the spectrum for networks that look similar to other mobile LTE networks. Meanwhile, some large enterprises may view the spectrum use for private LTE or in-building wireless services. Overall, we anticipate that CBRS infrastructure revenue will reach roughly $1B by 2024.



Note: Excludes revenue contribution related to fixed wireless access application

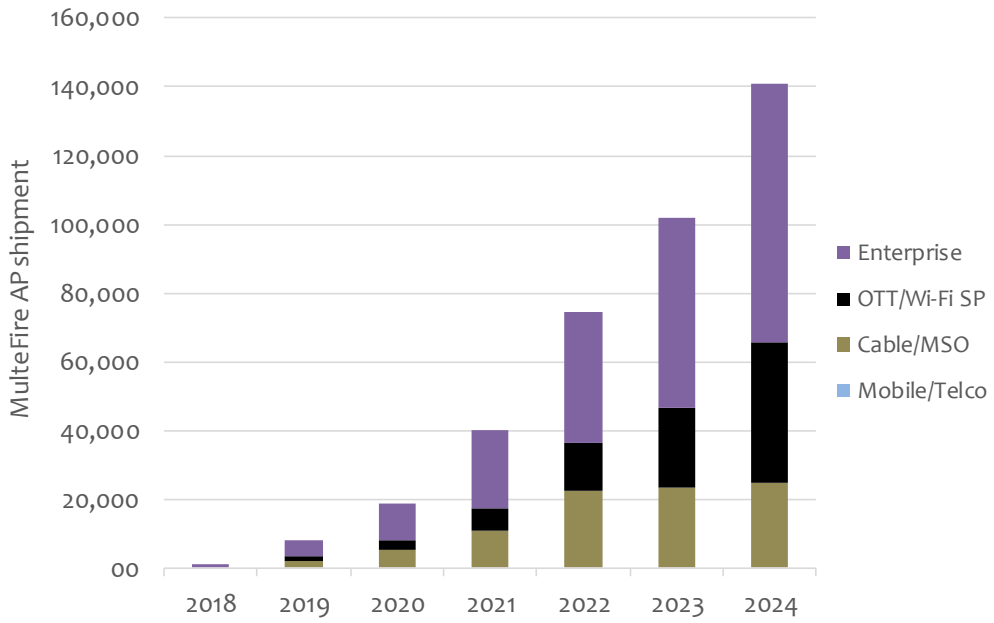
Source: Mobile Experts

Chart 16: Carrier CBRS Radio Equipment Revenue Forecast, 2018-2024

MulteFire (LTE-U) Shipment Forecast

Qualcomm introduced the MulteFire concept as a way for operators to use LTE instead of WI-Fi in unlicensed bands. They created a consortium and pushed on this idea for some years, but the adoption has been slow. Mobile operators in general are not willing to invest in infrastructure with control signals in the interference-prone unlicensed band, so the biggest source of support is not there. Cable operators are another possibility but their movement has been slow, and the critical US market is now focused on CBRS. OTT players and the global market in the 5 GHz band remains one possible source of support for this concept.

In the end, we believe that the operators are finding ways to use licensed bands for an anchor, but the emerging Enterprise/Private LTE market may be a way for LTE-U or 5G-U to finally succeed. The below forecast assumes that either LTE or 5G is adopted in unlicensed bands by industrial enterprises for automation or internal broadband applications.

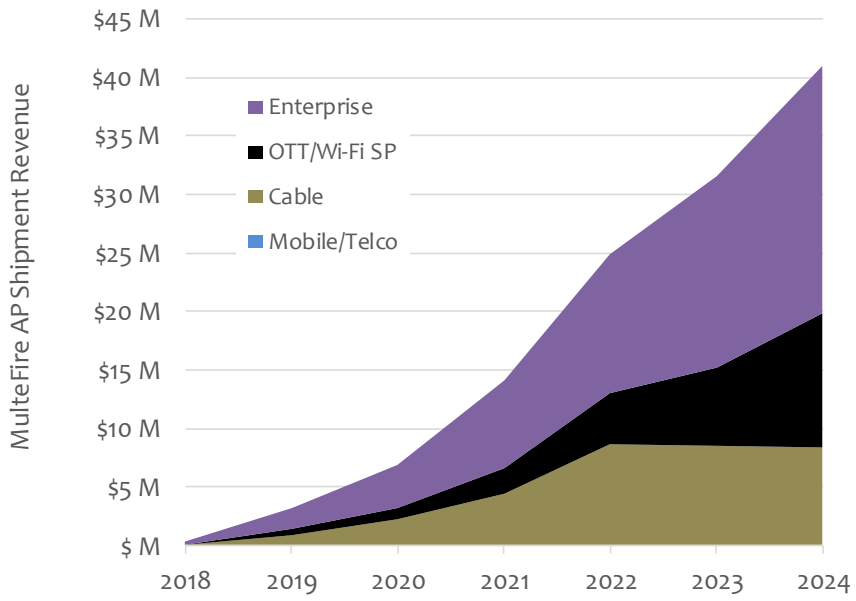


Source: Mobile Experts

Chart 17: MulteFire AP Shipment Forecast by Operator Segment, 2018-2024

MulteFire Revenue Forecast

The low numbers of shipments in the MulteFire category means that the equipment revenue will also be quite low. We consider this market to be far too small to support ongoing investments in chipsets and software solutions, so it's likely to die from lack of support in the supply chain over time.



Source: Mobile Experts

Chart 18: MulteFire Equipment Revenue by Operator Segment, 2018-2024

LTE-U and 5G-U

As 5G comes into play in the licensed bands, of course any customer for LTE-U will want to use the 5G NR waveform as well. Everybody wants to invest in the "latest and greatest" standard, to avoid being left behind. In our forecasts, we're projecting shipments and revenue for MulteFire in general, but we expect some mixture of LTE-U and 5G in the unlicensed bands, shifting gradually to 5G-U in time. Because the market for purely unlicensed carrier investment is pretty small, we consider the transition to 5G-U to be fairly unpredictable in terms of timing of chipset investments and supporting software.

7 ACRONYMS

2G: Second Generation Cellular

3G: Third Generation Cellular

3GPP: Third Generation Partnership Project

4G: Fourth Generation Cellular

5G: Fifth Generation Cellular

5G-U: 5G in unlicensed bands (a broad term including 5G versions of LAA and MulteFire)

802.1x: A security platform standard established by IEEE.

802.11: An umbrella standard which encompasses multiple unlicensed communications standards within the IEEE.

802.11a/b/g: Early generations of the 802.11 standard.

802.11n: The current generation of the 802.11 standard.

802.11ac: The generation of the 802.11 standard introduced in 2013.

802.11ad: An IEEE standard for 60 GHz short-range communications.

802.11ah: An IEEE standard for unlicensed communications below 1 GHz.

802.11ax: A future IEEE standard for very high throughput in Wi-Fi.

802.11ay: The next-generation 802.11ad that operates in 60 GHz band.

802.11i: An IEEE security specification for Wi-Fi networks.

802.11k: An IEEE standard for radio resource management to assist in limited mobility.

802.11r: An IEEE standard for rapid transition from one AP to another.

802.11u: The IEEE standard associated with Hotspot 2.0.

AAA: Authentication, Authorization, and Accounting (typically refers to the server which performs these functions).

AC: Alternating Current or Access Controller.

ACK: Acknowledgement.

AES: Advanced Encryption Standard.

ANDSF: Access Network Discovery and Selection Function.

Android: Google's mobile device operating system.

AP: Access Point (often referring to Wi-Fi access point)

APN: Access Point Name

ARPU: Average Revenue Per User

BAS: Broadcast Auxiliary Service (internal RF system used by a TV/radio station for backhaul channels from field to station)

BSC: Base Station Controller

BTS: Base Transceiver Station

Bits/Hz/sec: Digital bits transmitted per Hertz of bandwidth per second

CA: Carrier Aggregation

CARS: Cable Television Relay Service (internal microwave systems used by cable and other pay TV operators)

CBRS: Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US

CPE: Customer Premise Equipment (e.g., cable modem, broadband gateway)

dBm: Decibels of power relative to 1mW

DRS: Distributed Radio System

DSL: Digital Subscriber Line

EAP: Extensible Authentication Protocol.

EAP-AKA: EAP via Authentication and Key Agreement.

EAP-SIM: EAP via Subscriber ID Module.

EAP-TLS: EAP via Transport Layer Security.

EAP-TTLS: EAP via Tunneled Transport Layer Security.

EMEA: Europe, Middle East and Africa

eNB: eNodeB, or the radio access node for LTE

EPC: Evolved Packet Core.

ePDG: Evolved Packet Data Gateway.

GAA: General Authorized Access, applicable for the 3.5GHz shared spectrum, the lowest priority access, similar to unlicensed spectrum use

GB: Gigabyte

Gbps/km2: Gigabits per second per square kilometer

GHz: Gigahertz

GSM: Global System for Mobile communications, a 2G radio interface

GTP: GPRS Tunneling Protocol

GW: Gateway (normally referring to a femto gateway)

HARQ: Hybrid Automatic Repeat Request

HetNet: Heterogeneous Network

HEW: High-Efficiency Wireless (now renamed 802.11ax)

HLR: Home Location Register.

HSPA: High-Speed Packet Access

HSPA+: A subsequent evolution of HSPA with higher throughput

HSS: Home Subscriber Server

Hz: Hertz (cycles per second)

IEEE: Institute of Electrical and Electronics Engineers

IETF: Internet Engineering Task Force

IKEv2: Internet Key Exchange (version 2)

IP: Internet Protocol

IPSec: Internet Protocol Security

IPv4: Internet Protocol version 4

IPv6: Internet Protocol version 6

I-WLAN: Interworking for Wireless Local Area Networks.

LAN: Local Access Network

LTE-A: LTE Advanced, a higher bandwidth version of LTE

LAA: LTE-License Assisted Access, a 3GPP-compliant "official" LTE-U technology

LTE: Long Term Evolution, a "4G" radio interface based on orthogonal frequency division multiplexed data

LTE-U: LTE-Unlicensed, an "unofficial" technology to run LTE waveform on 5GHz unlicensed spectrum band

LTTS: Long Television Transmission Service (relay television programming between points)

LWA: LTE/Wi-Fi Aggregation (use of LTE signals on both licensed control channels and licensed data channels, and Wi-Fi signals on unlicensed data channels).

MAC: Media Access Control layer

MHz: Megahertz

MIMO: Multiple Input, Multiple Output

MNO: Mobile Network Operator

MSO: Multi-Service (or System) Operator (reference to a cable operator)

MVNO: Mobile Virtual Network Operator

MulteFire: Standalone LTE-U technology whereby both control and data plane traffic flows in an unlicensed band

MU-MIMO: Multi-User MIMO.

NGH: Next Generation Hotspot (Hotspot 2.0)

OEM: Original Equipment Manufacturer

OFDM: Orthogonal Frequency Division Multiplexed

OFS: Private Operational Fixed Microwave Service (governed by Part 94 of FCC rules)

PAL: Priority Access License, applicable for the 3.5GHz band, second highest priority in use of the 3.5GHz shared spectrum

Passpoint: A certification stamp for Hotspot 2.0 equipment, administered by Wi-Fi Alliance

PC: Personal Computer

QoS: Quality of Service

RAN: Radio Access Network

RF: Radio Frequency

SAS: Spectrum Access System, a software system to coordinate spectrum sharing (although it can be applied across all shared spectrum, its use is primarily focused on 3.5GHz CBRS)

SIP: Session Initiation Protocol

SNR: Signal-to-Noise Ratio

SSID: Service Set Identification

TD-LTE: Time Domain based Long Term Evolution

UE: User Equipment

U-NII: Unlicensed National Information Infrastructure

VAR: Value Added Reseller

W: Watts

WCDMA: Wideband Code Domain Multiple Access, a 3G radio interface

Wi-Fi: Wireless Fidelity (802.11 data communications)

WISP: Wireless Internet Service Provider

WLAN: Wireless Local Area Network

8 METHODOLOGY

This year, as Mobile Experts tracks the unlicensed radio market we do not see many areas where our 2018 expectations have changed. We've updated our forecasts with fresh information about actual deployments but the numbers of sites and usage of LAA/MulteFire/Wi-Fi have been pretty accurate. Overall, this year's update is a simple refresh of the 2018 report.

Mobile Experts has investigated the entire ecosystem for Wi-Fi in public areas, with segmentation that is different than other market analysis. In this study, we cover Wi-Fi equipment deployed by an "operator", meaning a company that provides a public wireless access service, as well as large venues such as stadiums, airports, military bases, and even city deployments. These non-carrier participants are included because Hotspot 2.0 enables all of these entities to interwork via roaming agreements in the same way, and the equipment is likely to look very similar.

Small cells with integrated Wi-Fi are included in this analysis. In particular, Mobile Experts has assumed that many indoor licensed small cells will also include Wi-Fi semiconductors. This forecast estimates the number of these Wi-Fi APs and the minority portion of the small-cell ASP which is devoted to unlicensed operation.

SCOPE OF CARRIER UNLICENSED RADIO:
A "Carrier Unlicensed Radio" unit can be either an Access Point (AP) or a Customer Premise Equipment (CPE) unit that primarily operates in unlicensed or shared spectrum bands. The Carrier Unlicensed Radio unit can operate using either Wi-Fi based technology such as 802.11 n/ac/ax/ad/ay or LTE-based technology such as LAA, MulteFire, or CBRS/OnGo. Please note that Fixed Wireless Access AP and CPE equipment is not included in this report.

NOTES ON MARKET SHARE:
In the Mobile Experts forecast, "market share" designates the proportion of market revenue for each supplier. "Shipment share" denotes the proportion of total shipments from each supplier. In general, Mobile Experts uses market share for semiconductors and for software because revenue tracking is more straightforward than other measurements. However, in the case of network elements such as Access Points or Wi-Fi networks, the revenue from software and service creates confusion and "shipment share" provides a more trackable, straightforward metric.

Figure 15 gives the detailed definitions for each category of equipment, for regions of the world, and for specific segments of Carrier Unlicensed Radio equipment.

LTE Unlicensed	Known as LTE-U. Defined by the LTE-U Forum and led by Verizon in cooperation with Alcatel-Lucent, Ericsson, Qualcomm Technologies, Inc., and Samsung. LTE-U base stations and consumer devices leverage unlicensed frequencies in the 5 GHz (UNII-1 and UNII-3) bands as data channels, with the LTE control plane operating across licensed frequencies. LTE-U is based on 3GPP's already published Release 10 and later specifications. LTE-U extends the benefits of LTE and LTE Advanced to unlicensed spectrum, but without a Listen-Before-Talk schema.
CSAT	Carrier Sensing Adaptive Transmission essentially uses a duty cycle to turn LTE on and off. The duty cycle can be adaptive but many examples refer to a 1/3 duty cycle for LTE transmission.
Listen-Before-Talk	A mechanism for contention mitigation. LBT systems can more fairly share spectrum with heterogeneous standards and not dominate a wireless channel.
Licensed-Assisted Access	Known as LAA. Like LTE-U, LAA leverages unlicensed spectrum for data in the 5 GHz (UNII-1 and UNII-3) bands as data channels, with the LTE control plane operating across licensed frequencies. LAA offers support for Listen-Before-Talk. Ratification by 3GPP is expected in Release 13 in March 2016.
LTE/Wi-Fi Aggregation	Known as LWA. LTE/Wi-Fi Aggregation uses Wi-Fi (802.11ac, etc.) in 5 GHz data channels, with the LTE control plane operating across licensed frequencies. Because it uses standard Wi-Fi protocols, it is less likely to disrupt existing systems. Ratification by 3GPP is expected in Release 13 in March 2016.
Citizen Broadband Radio Service	Known as CBRS. 150 MHz of 3.5 GHz shared spectrum band allocated in the USA for use in TD-LTE primary access or in LAA manner as a secondary cell
MulteFire	Standalone LTE operation in unlicensed band without the need for the "anchor" carrier in a licensed spectrum band.

Source: Mobile Experts

Figure 15. Detailed Technical Definitions of Access Technologies